and left unfilled to facilitate passage of air currents. The annular space between the outer and inner walls of this structure was filled with potatoes and left open at the top. Another structure was horizontal and rectangular, with dimensions 16′ x 4′, and situated 1½ feet above the ground. Potatoes were placed in this structure in 4′ x 4′ areas and at depths of 2″, 4″, 8″ and 12″, with the top left uncovered.

The potatoes froze soon after being placed in the open and did not thaw to any extent for nearly eight weeks. Figures 1, 2, and 3 illustrate how the potatoes were spread and how they shrank during freeze drying. By mid-April, the tubers had shrunk approximately 50 per cent of their original volume. Those in thin layers and on top of thicker layers were soft and had an odor similar to silage. Potatoes lying underneath in the thick layers were largely unfrozen at this time. Additional potatoes were spread in April to see if mild, spring freezes would bring about dehydration. This however, was unsuccessful.

In mid-June, the potatoes had shrunk to approximately one-third of their original volume. No decay was present. It is believed that freeze-dried potatoes are preserved by a fermentation, the products of which inhibit microbial activity that would destroy the tissue. Examination indicated the presence of acid-forming bacteria and of higher acid concentration than ordinarily found in potatoes. The June examination disclosed that tubers in thin layers (two and four inches thick) were firm, but those in 8- and 12-inch layers were soft beneath the surface. Tubers underneath the outer layer in the cylindrical crib were soft, having the consistency of potato silage.

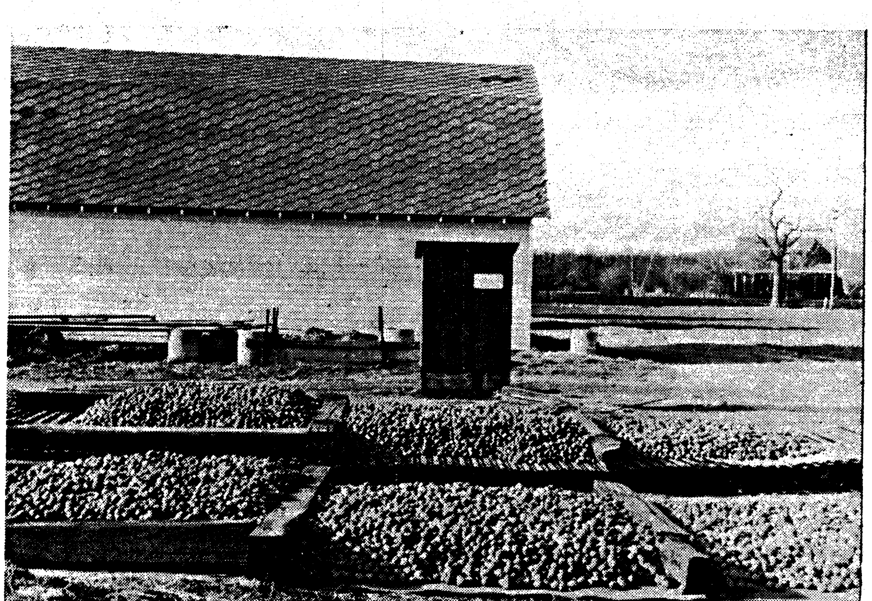

FIGURE 1.—Experimental lots of potatoes spread during winter at 12-, 8-, and 4-inch depths on racks and on the ground. Before freezing and thawing. (Photograph by H. S. Cunningham, Long Island Vegetable Research Farm, Riverhead, N. Y.)

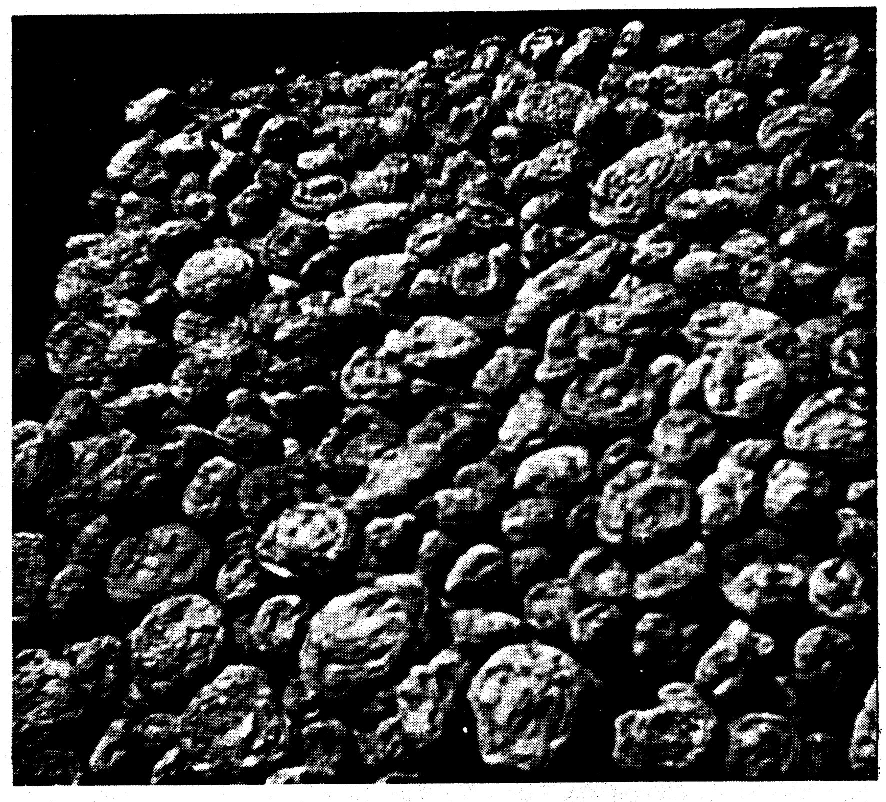

FIGURE 2.—Potatoes in early spring, partially dried by freezing and thawing. Note shriveling.

Precipitation, in inches, was as follows at Presque Isle from February 1 until observations were stopped in the middle of June: February, 1¾; March, 2¼; April, 2½; May, 1; and June, 2 inches.

Nutrient Losses in the Field Experiments

Losses in total solids and in various nutrients were ascertained by measuring weight losses that occurred during exposure of the potatoes and by determinations of moisture and of other constituents. Losses of sugars, nitrogen compounds, inorganic compounds (as gauged indirectly by ash determinations), and crude fiber were nearly the same for potatoes stored in the open racks at 4-, 8-, and 12-inch thicknesses. These determinations were made by methods of the Association of Official Agricultural Chemists. (4) Total loss of these substances was 81-82 per cent. No determinations of pectin, organic acids, fat, and minor constituents were made. The starch loss in the 4-inch layer of potatoes was much less than in the 8- and 12-inch layers. Because of this differential in starch loss, loss of total solids during freeze drying was only 28 per cent in the 4-inch layer as compared to 38 per cent in the 8- and 12-inch layers.

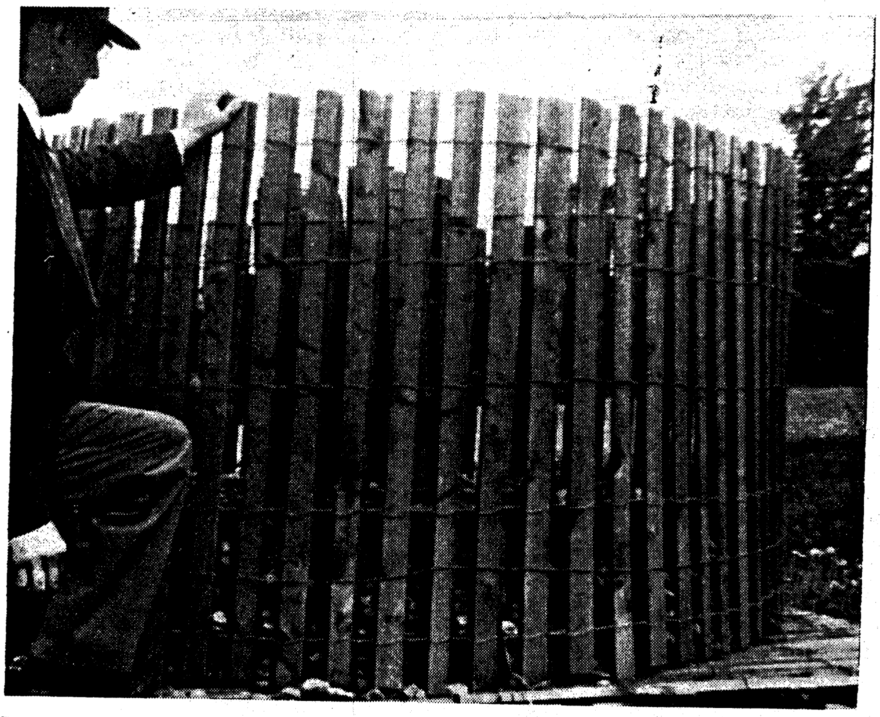

FIGURE 3.—Potatoes reduced to one-third their original volume after freezing and thawing during winter and spring.

Data on nutrient losses that occurred during natural freeze drying of potatoes in a 4-inch layer are presented in table 1.

It is seen that nearly all the sugars disappeared from the potatoes and most of the nitrogenous and inorganic compounds. About one-third of the crude fiber and 8 per cent of the starch disappeared.

TABLE 1.—*Nutrient losses during natural freeze drying of potatoes.*[1]

	100 Lbs. Potatoes Potatoes, Lbs.	29.5 Lbs. Product[3] Product,[3] Lbs.	Loss Per cent
Total Solids	18.0	13.0	28
Starch	12.6	11.6	8
N Compounds[2]	2.5	0.4	84
Sugars	1.30	0.04	97
Ash	1.13	0.25	78
Crude Fiber	0.47	0.31	34

[1]Potatoes in 4-inch layer in open, ventilated rack above ground. At Presque Isle, Maine, February 7 to June 15, 1950.
[2]Total Nitrogen X 6.25.
[3]56 per cent Moisture.

Undoubtedly much of the nutrient substances that disappear from the potatoes during freeze drying are lost by juice leakage. Some of the nutrient material is lost by liberation of full-strength juice from the potatoes, whereas additional quantities are leached from the tubers during rains and thaws following rains. As previously mentioned, a good part of the juice is evidently utilized as fertilizer by grass if the tubers are spread on pasture. The fraction of the potato nutrients converted to volatile compounds by fermentation, however, is lost for all practical purposes.

It will be noted that the product of natural freeze drying, the composition of which is given in table 1, contained 56 per cent moisture. Even at this relatively high moisture content, the product appeared fairly stable when kept in the open grass under conditions prevailing in the summer in northern Maine. But if freeze-dried potatoes of that moisture range are piled up or confined in a container from which heat cannot readily escape, they will undergo rapid and extensive fermentation.

It is apparent that potatoes dried by freezing and thawing must be dehydrated to approximately 20 per cent moisture content to obtain storage stability.

A new lot of potatoes was spread in the open in November 1950 at Aroostook Farm. These potatoes were placed six to eight inches deep on asphalt felt that covered the ground. Upon examination in June 1951, the tubers were found to be partially dehydrated and free from decay. Their moisture content was estimated to be about 50 per cent at that time. Since no animals were available at Aroostook Farm for experimental feeding, it was planned to ship the product to the principal unit of the Experiment Station at Orono where the Department of Animal Industry is located. Although the partially-dehydrated potatoes were left out throughout the summer of 1951, which was unusually wet at Presque Isle, the product did not become sufficiently dry to permit packaging for shipment. It was then decided to leave the product exposed until spring 1952. Following this year and one-half exposure, it was found that extensive nutrient losses caused by juice leakage and fermentation had left very little of the potatoes except the skin. Therefore, it was concluded that is it not practicable to dry potatoes to stable form (20 per cent moisture or less) by natural conditions in northern Maine.

Dehydration of potatoes by alternate freezing and thawing was also carried out in the laboratory. Although controlled conditions are much different from natural conditions during winter and spring, an advantage was gained in that progressive dehydration could be followed over a series of cycles of freezing and thawing in a relatively short time. In the laboratory, the transformation between the frozen and thawed states was much more rapid than in the outdoors and the potatoes at all times were in a sheltered, relatively dry atmosphere.

The potatoes used in the laboratory freeze drying experiment were of relatively low solids content and all within the 1.045 to 1.055 specific gravity range. They were placed in two wire baskets holding about 30 pounds each. Samples were removed from only one of the baskets so that accumulated weight loss data could be obtained from the other. Results are given in table 2.

Much more juice was lost during the first than in subsequent cycles of freezing and thawing. Weight loss was slight while the potatoes

TABLE 2.—*Progressive weight loss during laboratory dehydration of potatoes*[1] *by alternate freezing and thawing.*[2]

Cycle Number	Weight Loss, of Original
	Per cent
1	22.6
2	5.2
3	3.1
4	3.2
5	2.8
7	1.2

[1]Original moisture content, 84.4 per cent. Total weight loss after 9 cycles of freezing and thawing plus continuous drying at room temperature, 83 per cent. Final moisture content 18.4 per cent.
[2]In freezer 0°F. overnight, followed by exposure to room temperature during the day to complete cycle.

were in the frozen state. For example, in the first cycle, the tubers lost 0.9 per cent of their original weight (presumably, mainly by sublimation of ice) during the freezing phase and 21.7 per cent during thawing. There was a 45 per cent decrease in weight during nine cycles of freezing and thawing, taking place over a period of three weeks. Following this, the potatoes were left out at room temperature for five weeks. The loss during this final treatment, amounting to 38 per cent of the original weight, was by evaporation only, since no more juice escaped.

The data in table 3 show the nutrient losses that occurred during freeze dehydration in the laboratory. Losses of total solids and non-starch solids were almost one-third of those experienced in field dehydration. Loss of starch was nil. Apparently there was much less fermentation of nutrients under laboratory conditions.

TABLE 3.—*Nutrient losses during laboratory freeze-drying*[1] *of potatoes.*

	100 Lbs. Potatoes Potatoes, Lbs.	17.0 Lbs. Product[2] Product,[2] Lbs.	Loss Per cent
Total Solids	15.6	13.9	11
Starch	10.9	11.1	—
N Compounds[3]	2.12	1.17	45
Sugars	0.13	0.01	92
Ash	0.96	0.49	49
Crude Fiber	0.53	0.53	0

[1]Nine cycles, over period 21 days, of freezing at 0°F, followed by thawing at 75°F. After this, potatoes allowed to dry at 75°F. for 35 days.
[2]18.4 per cent moisture.
[3]Total N X 6.25.

Microscopical Examinations of Tubers

Microscopical techniques were used in the search for an explanation of the mechanism of juice leakage caused by freezing and thawing and of the low starch loss in the presence of high losses of other nutrients. Samples of potato tissue were studied under a dissecting microscopic,

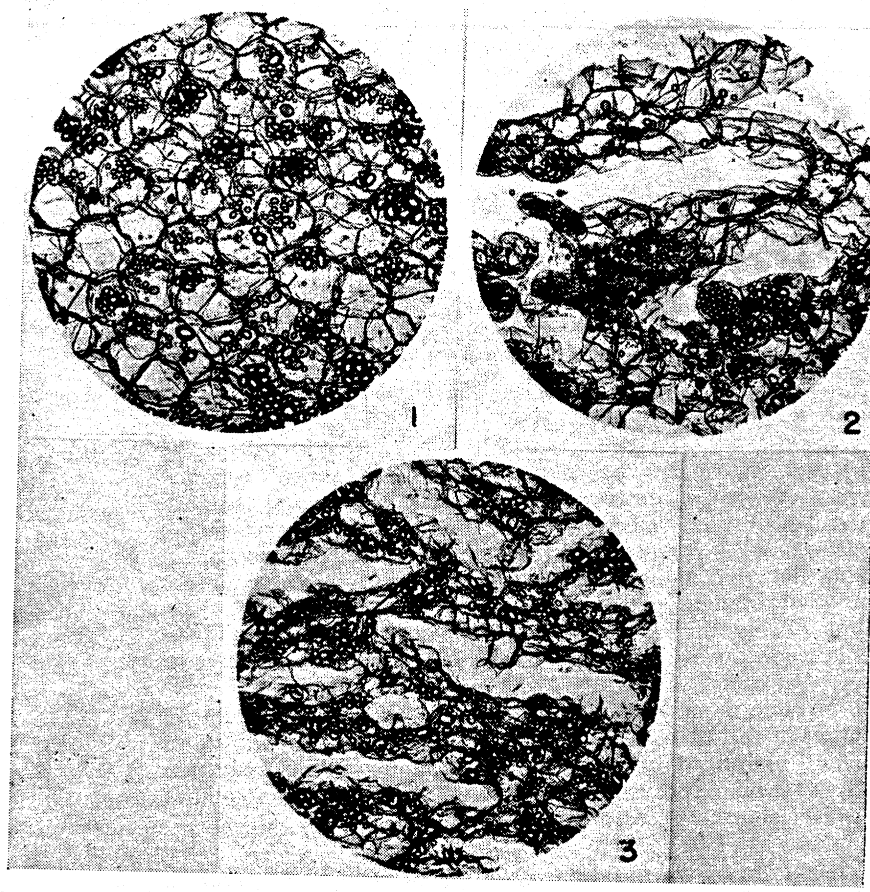

FIGURE 4.—Tissue changes during freezing and thawing of raw potato. Sections 120 microns thick from pith region. Magnification 52X. 1. Untreated potato. 2. First thaw. 3. Third thaw.

and observations made on the cells and tissues as they were subjected to tension and pressure. Observations were made on different regions of the tubers, under different conditions of illumination and at various magnifications. Sections 120 microns thick were prepared from the pith region with the freezing microtome. These were stained and used for making the photomicrographs shown in figure 4.

The following tentative conclusion was made. When a potato is frozen, its tissues expand. For several reasons, among which is the fact that the tissues are not homogeneous throughout their volume with respect to water content and osmotic pressure of cell sap, tissue expansion is greater or more rapid in some regions than in others. Because the tissues contain very little intercellular air which might accommodate or cushion the different rates of expansion, the stresses are transferred directly to the cell walls and intercellular cement. In numerous regions the intercellular cement gives way and groups of cells are sheared from other groups. For the most part no cells or cell walls are broken, and the starch remains within the cells.

When thawing occurs, sap diffuses from the cells, since the differential permeability of the cell protoplasmic membrane is destroyed by freezing. The cells lose their turgor and the tissues become flaccid. The sap moves into the spaces formed by the shearing apart of cell clusters. This results in a continuous network of channels filled with cell sap. Where the network contacts permeable regions of the potato skin, such as occur in the vicinity of eyes, lenticels, and bruised areas, sap is lost and the tissues contract.

The major damage to tissue structure occurs during the first freeze. Subsequent thawing and freezing treatments apparently cause no more rifts in the tissues, but merely bring about a contraction of those already present. In regions where the intercellular cement is not fractured, the cement remains adequately strong, as is evidenced by the high coherence of tissues.

Photomicrographs given in figure 4 illustrate the progressive changes in tissue that occur during the freezing and thawing of raw potatoes. In the original unfrozen tuber (Figure 4,1.), the cells are tightly stuck together and the tissue is coherent. There is almost no intercellular air. Since the section on the average is about one cell thick, many cells not in the proper plane have been cut open and have thereby lost their starch granules.

After the first freeze (Figure 4,2), the separation of cell clusters and development of channels in the tissue is evident. It is clear that very few cells break, since the cell contours bordering the channels are smooth and the uncut cells contain their original amount of starch granules. This point is corroborated by micro-dissection studies on whole, uncut tissues. After the third thaw (Figure 4,3), a pronounced shrinkage of the tissues and channels is evident. The spatial relationship between the channels and cells, however, is not much different from that in tubers frozen only once.

Fermentation Raw Material

Although it is envisioned that the principal use of freeze-dried potatoes lies in feed, utilization as raw material for fermentations has also been considered. William M. Case, while Executive Secretary of the Red River Valley Potato Growers' Association, suggested that this product be evaluated in alcoholic fermentation. A trial was carried out using field-dried potatoes from the Maine experiment (Table 1), which had been further dehydrated by storing inside. At the time these potatoes were evaluated in alcoholic fermentation at the Northern Utilization Research Branch, they had the following composition in percentages: Moisture, 13.9; starch, 76.6; nitrogen compounds, 2.9; crude fiber, 2.1; ash, 1.8; total sugars, 0.3. A yield of 4.95 proof-gallons of alcohol was obtained per 56 pounds "mash bill" with malt conversion and 5.30 proof-gallons with *A. niger* NRRL 337 (Fungal amylase) conversion. Corn of moisture content comparable to the dehydrated potatoes yields about 5.6 proof-gallons of alcohol per bushel (56 lbs.). Hence, the yield of alcohol from field-dehydrated potatoes was considered rather satisfactory.

Long Island Experiments

Cooperative trials in freeze dehydration between the Eastern Utilization Research Branch and the Long Island Vegetable Research Farm of Cornell Agricultural Experiment Station were conducted in 1950 at Riverhead, New York. Potatoes were exposed in various ways in late February and left out until mid-summer. Some of the tubers were spread on uncovered ground, others on asphalt felt, whereas the remainder of the tubers were suspended on open racks 10 inches above the ground in 4-, 8-, and 12-inch layers. At least four severe freezes occurred before spring, and considerable juice was liberated from the potatoes. The moisture content had been reduced from an original 83 per cent to as low as 43 per cent in one lot by late July. Lowest moisture content was attained with the 4-inch layer on the ground. Total precipitation was about 15½ inches during the five months over which observations were made.

Although the potatoes spread at Riverhead did not decay, the tubers fermented badly in the late spring as they lay on open sand, exposed to the hot sun. This excessive fermentation, with accompanying heavy loss of nutrients, was much more severe than experienced in northern Maine grassland. Thus, it appears questionable that freeze drying of potatoes would be feasible on Long Island.

Summary and Conclusions

Natural freeze drying of potatoes, when properly carried out, seems practicable in northern areas for converting cull potatoes into a partially stable feed and consequently extend the potato feeding period into late spring and early summer. Potatoes on open racks lost 30-40 per cent of their total solids during this process. Most of the solids lost from the tubers were non-starch substances. Dissolved solids in the juice, upon entering the soil, provide tremendous stimulation to growth of grass. Therefore, apparently much of the solids lost by the tuber are gained by the soil as fertilizer. Laboratory experiments in alternate freezing and thawing resulted in a loss of only approximately 10 per cent total solids. This lower solids loss is thought to be a consequence of the reduced fermentation experienced under laboratory conditions.

Microscopical examination showed that freezing causes groups of cells to shear apart from other groups. After thawing, juice passes through the now permeable cell membranes and escapes through a network of canals between the separated cells. Very little starch is lost in the liberated juice because the potato cells are not ruptured. The greatest loss of juice (23 per cent of original weight of potatoes in a laboratory experiment) occurred during the first thaw. Juice loss decreased during subsequent cycles until only 1 per cent was lost during the seventh cycle.

Spreading potatoes on the ground is apparently more practicable than placing them in a vertical crib or in open, horizontal structures above the ground. Spreading potatoes in layers no more than six to eight inches in depth is better than in deeper layers. The potatoes should be spread in a pasture early enough in the winter to assure exposure to severe freezes. From the experience of livestock men in the Red River Valley and in Maine, apparently the most feasible method of using the field-dehydrated potato feed is to let the animals pick up the tubers from the ground.

Indications are that field-dried potatoes can be used for fermentations as well as for feed. A good yield of alcohol was obtained upon fermenting such potatoes.

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NATURAL DEHYDRATION OF CULL POTATOES BY ALTERNATE FREEZING AND THAWING[1]

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Drying of potatoes by alternate freezing and thawing was apparently originated nearly 2,000 years ago by inhabitants of the highland country of western South America. (5) Archeological proof is available in the existence of ornamental pots shaped in the form of dehydrated potatoes and in the recovery of dried potatoes that are well preserved after many centuries. Pots unearthed in the northern, coastal area of Peru are believed to date back to approximately 200 A.D. Dried potatoes are frequently found in the pre-Columbian graves of the arid coastal zone.

In dehydrating these potatoes, tubers were spread on the ground of high plateaus where they froze during the night and thawed during the day. Much of the juice was lost during the thaws. After four or five days of freezing and thawing, the natives trampled on the potatoes to expel most of the remaining juice. Following this treatment, the potatoes were left 15 to 20 days longer to undergo further dehydration by action of sunlight and frosts. This product, called *chuño,* consisted of hard, dark, shrivelled potatoes that had been greatly reduced in volume and weight as a result of natural dehydration. It was used, as such, for animal feed.

For food use, preparation of the dehydrated potatoes was modified to give a nearly white product called *tunta* or "moray." After partial dehydration by freezing and thawing, the potatoes were placed in a pool or stream of cold water and allowed to remain for one to two months. They were then dried in the sun about one week. Extraction of the dark substances gave an attractive product that could be ground into flour for baking or reconstituted in water to be cooked and served in various forms instead of fresh potatoes. Preparation of *chuño* and *tunta* continue up to the present time in the plateau region of western South America.

This dehydration practice of the early South Americans seems to have been largely forgotten in the United States until 1946 when a group of North Dakota potato growers, led by William M. Case, tried the idea there. Cull potatoes were spread on pasture and allowed to freeze and thaw during the winter and spring. Late in the spring, livestock were let out to pasture to eat the dried potatoes. Both dairy and beef cattle did well in the North Dakota demonstration, with dried potatoes supplying an important part of their rations. The grass stand where the potatoes had been placed improved noticeably as the result of nutrients that had drained onto the soil.

Despite the facts that natural freeze drying[4] of potatoes had been

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[4]The terms "freeze drying" and "freeze dried" as used in this paper refer, respectively, to a method of dehydrating potatoes by alternately freezing and thawing them, and to the resulting product.

practiced for several centuries in South America and in recent times has been demonstrated to be successful in northern North Dakota — where winters are severe, humidity low, and annual precipitation averages only about 20 inches — there is still a need for more information. Of particular importance are such questions as the following: What quantities of the various nutrients are lost from the tubers during freeze dehydration? What is the nature of freeze and thaw dehydration? What are the most feasible conditions for carrying out the natural freeze dehydration of potatoes?

Hence, the Eastern Utilization Research Branch in cooperation with the Maine Agricultural Experiment Station initiated a series of trials at Presque Isle, Maine, in February 1950 which continued until the summer of 1952. Data were obtained on the optimum method of exposing the potatoes and certain observations made on the mechanism of freeze drying and on the nutrient loss.

Feeding of Freeze-Dried Potatoes

Although we have not been directly connected with controlled experiments in the feeding of freeze-dried potatoes, all available evidence points to the conclusion that the product is palatable to livestock and without any accompanying bad effects. Following the initiation of our experiments in Maine, several potato growers there conducted satisfactory demonstrations. One grower spread five carloads of potatoes on grassland near Presque Isle, Maine, in February 1950. The partially-dried product was fed successfully the following spring to beef and dairy cattle. (3) The same grower continued trials the following year, this time feeding the product to swine. Another grower near Presque Isle experienced favorable results in feeding freeze-dried potatoes; in the fall of 1951, he put out 30,000 bushels of culls for conversion to dry feed.

More recently, controlled experiments in feeding freeze-dried potatoes have been conducted by T. M. McCall, Superintendent of the Northwest School and Experiment Station, University of Minnesota, at Crookston, Minnesota. (2) McCall and associates observed that steers ate the field-dried potatoes readily and that grass growth was greater where the potatoes had been spread. Homer D. Fausch of the Northwest School and Experiment Station has summarized the results of recent potato feeding trials in Minnesota. (1) In two out of three trials conducted with freeze-dried potatoes in 1951, 1953, and 1954, definitely better weight gains were obtained on the lot of steers fed on potatoes plus pasture than on the control lot fed on pasture alone.

Experiments at Presque Isle, Maine

On February 1, 1950, potatoes were placed in the open at Aroostook Farm of the Maine Agricultural Experiment Station under several sets of conditions. Some were spread in layers 4, 8, and 12 inches deep on the ground, and others were placed in well-ventilated structures above ground. One of these structures was cylindrical, about eight feet in diameter and four feet high. It was constructed of snow fence reinforced with wire. The cylinder was mounted on a base 1½ feet above the ground and fitted with a slatted bottom to permit drainage and aeration. An inner cylinder about two feet in diameter was fixed at the center